

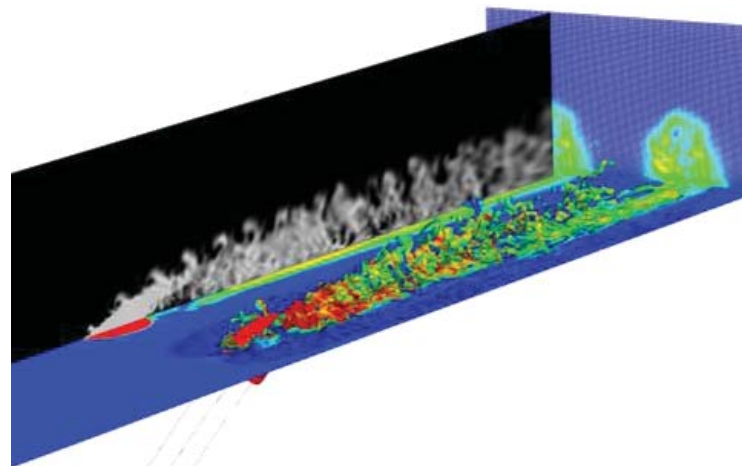
# **Development of the Glenn-HT Computer Code to Enable Time-Filtered Navier-Stokes (TFNS) Simulations and Application to Film Cooling on a Flat Plate Through Long Cooling Tubes**

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# Motivation

- Prediction of effectiveness/ heat transfer coefficient due to film cooling is fraught with inaccuracies and large variations using turbulence models.
- This is exacerbated at higher blowing ratios ( $M > 1$ )
- The high  $M$  regime is relevant to gas turbine blades.
- Good prediction in that environment is highly desirable to allow efficient use of coolant air and achieving high turbine efficiencies.

# Plan

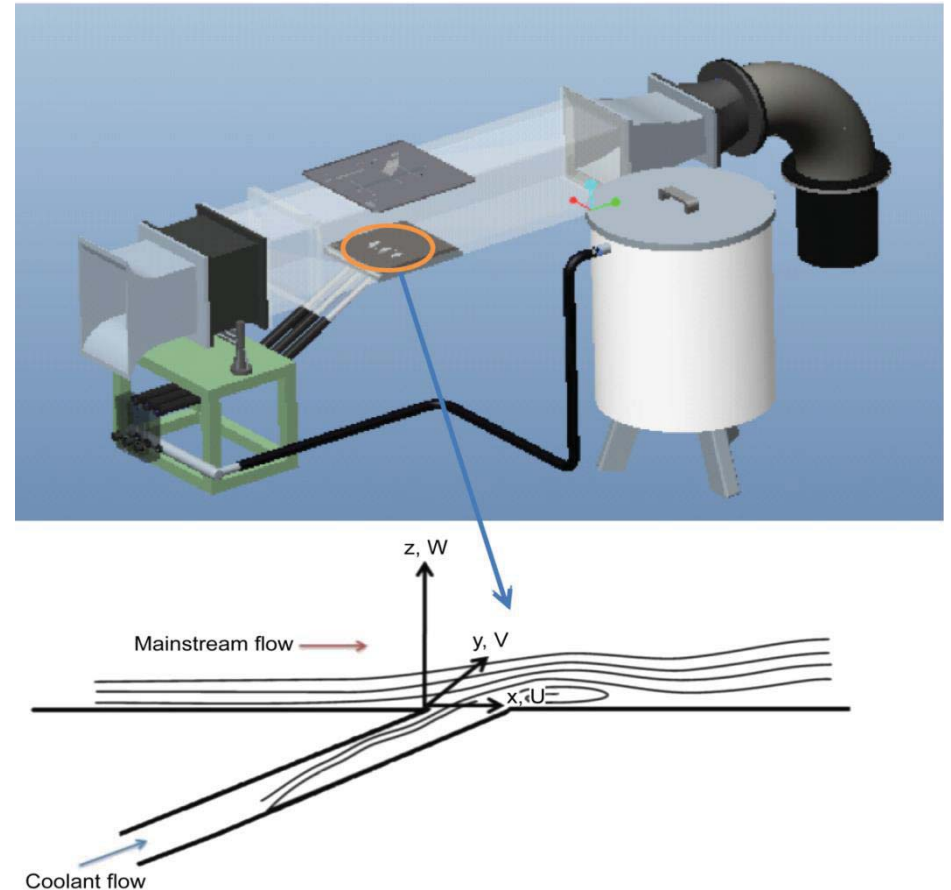
- Two-Pronged plan was conceived:
  - To perform accurate experiments measuring film-cooling effectiveness and the relevant flows.
  - To come up with CFD practice that is efficient and accurate.

## Plan (Cont.)

- 30 times engine scale test facility
- A three hole ( $d=0.75''$ ) film-cooling arrangement was adopted with a pitch of  $3d$ 's and inclination angle of  $30^\circ$
- Effectiveness varies with  $L/D$  and thus  $L/D$  was chosen to be large  $=20$  to allow for fully developed flow in the tubes.
- This also removes the effect of the plenum flow shown to affect the results.

# Conditions

- Free Stream Velocity= 9.1 m/s
- Reynolds number based on tube dia.= 11,000
- Inlet Tu=1.5%
- $\delta_{99} = 0.67 \cdot d$  at  $X/d = -0.5$



# CFD Tool, Glenn-HT

- Full compressible Reynolds-Averaged Navier-Stokes Formulation and Conjugate Heat Transfer
- Multi-block structured grids
- Finite Volume formulation
- Second order central differencing, 4<sup>th</sup> order artificial dissipation with eigenvalue scaling or,
- Second order upwind schemes, Hunyh, AUSM
- Multi-stage explicit Runge-Kutta time integration with local time stepping
- Multi-grid convergence acceleration
- Dual-Time-Stepping for unsteady simulations
- Parallel processing via MPI

# Why TFNS

- TFNS (PRNS, VLES) or 'Time Filtered-Navier-Stokes,' is an unsteady method. (Liu and Shih)
- Developed to simulate large turbulent eddies.
- Used with RANS relevant grid resolutions in combustion simulations with success. (Liu and Shih)
- Larger timescales (lower frequencies) of the turbulence are directly calculated while the effects of the unresolved turbulence timescales are modeled by a dynamic equation system.
- Contents of both resolved and unresolved turbulence are regulated by a Filtering Control Parameter (FCP), which is related to the *width* of the temporal filter.

# More About TFNS

- TFNS equations and its subfilter model do not have grid spacing as a parameter in their formulations.
- Possible to achieve a grid-independent numerical solution for a fixed Filtering Control Parameter.
- TFNS enables performance of URANS, very large eddy simulations (VLES), LES, and even Direct Numerical Simulations (DNS) in a unified way through the judicious selection of the value of FCP and the appropriately refined grid.



# Filtering

- Filtering is done via: 
$$\bar{\phi}(t, x_i) = \frac{1}{\Delta_T} \int_{t-\Delta_T/2}^{t+\Delta_T/2} \phi(t', x_i) dt'$$
- The ratio  $\Delta_T/T$  is used to set the FCP.

$$\text{FCP} = f_i\left(\frac{\Delta_T}{T}\right) \approx 2\left(\frac{\Delta_T}{T}\right) - \left(\frac{\Delta_T}{T}\right)^2 \quad i = 1, 3, 5$$

- For example,  $\Delta_T/T = 0.16$  produces an  $\text{FCP} = 0.30$  is intending to **directly resolve turbulence scales responsible for about 70% of the total turbulent kinetic energy** and **model the rest** of the unresolved turbulence scales that contain about **30% of the total turbulent kinetic energy**.
- An FCP of 0.3 was used in our computations.

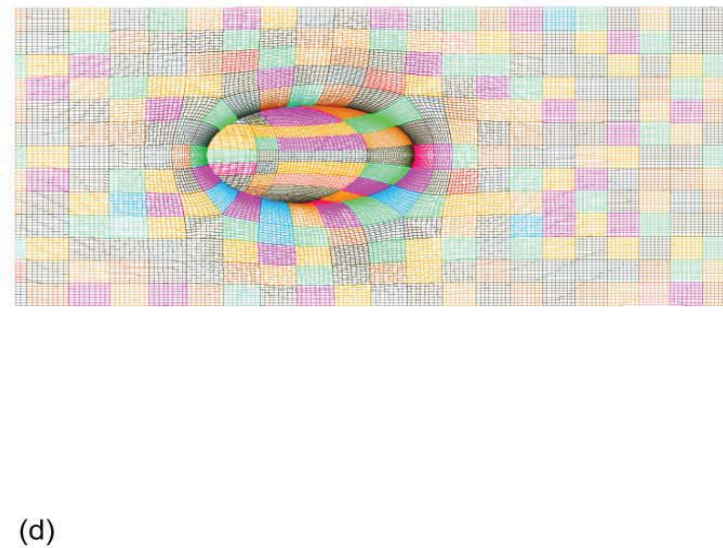
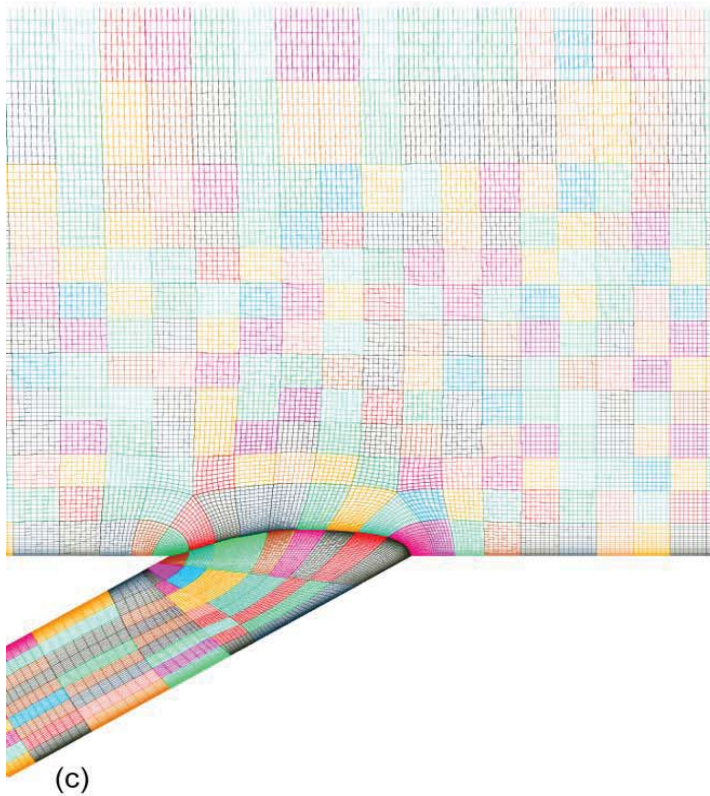
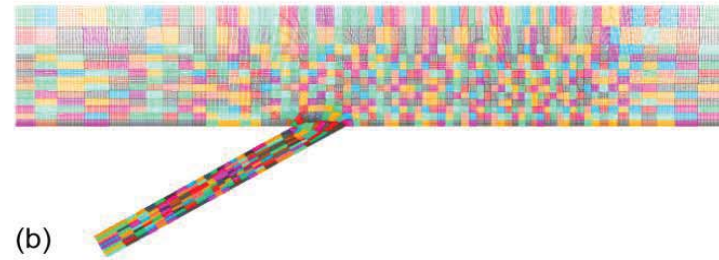
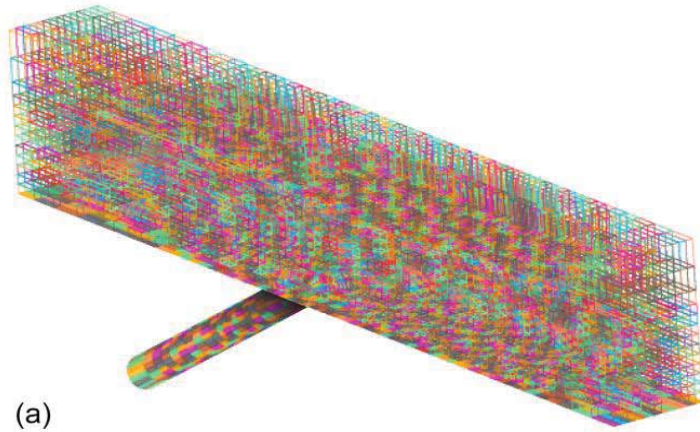
# Subfilter Model

- The subfilter model uses a relationship between the unresolved turbulent stresses (Reynolds) and the resolved turbulent flow field.
- In addition to the dissipative and diffusive effects accounted for through the eddy viscosity, the subfilter model accounts for the effects of anisotropy and rotation.

$$\tau_{ij} = -2f_1 \mu_T \left( \tilde{s}_{ij} - \delta_{ij} \tilde{s}_{kk} / 3 \right) + \frac{1}{3} \delta_{ij} \tau_{kk} - A_3 f_3 \bar{\rho} \frac{k^3}{\varepsilon^2} \left( \tilde{s}_{ik} \tilde{\omega}_{kj} - \tilde{\omega}_{ik} \tilde{s}_{kj} \right) \\ + 2A_5 f_5 \bar{\rho} \frac{k^4}{\varepsilon^3} \left[ \tilde{\omega}_{ik} \tilde{s}_{kj}^2 - \tilde{s}_{ik}^2 \tilde{\omega}_{kj} + \tilde{\omega}_{ik} \tilde{s}_{km} \tilde{\omega}_{mj} - \tilde{\omega}_{kl} \tilde{s}_{lm} \tilde{\omega}_{mk} \delta_{ij} + II_s \left( \tilde{s}_{ij} - \delta_{ij} \tilde{s}_{kk} / 3 \right) \right]$$

$$\overline{\theta u_i} = -\kappa_T T_{,i} - \kappa_T \frac{k}{\varepsilon} (C_1 S_{ij} + C_2 \Omega_{ij}) \quad ; \quad \kappa_T = \frac{\mu_t}{Pr_t}$$

# Computational Domain



# Computational Details

The computational domain:

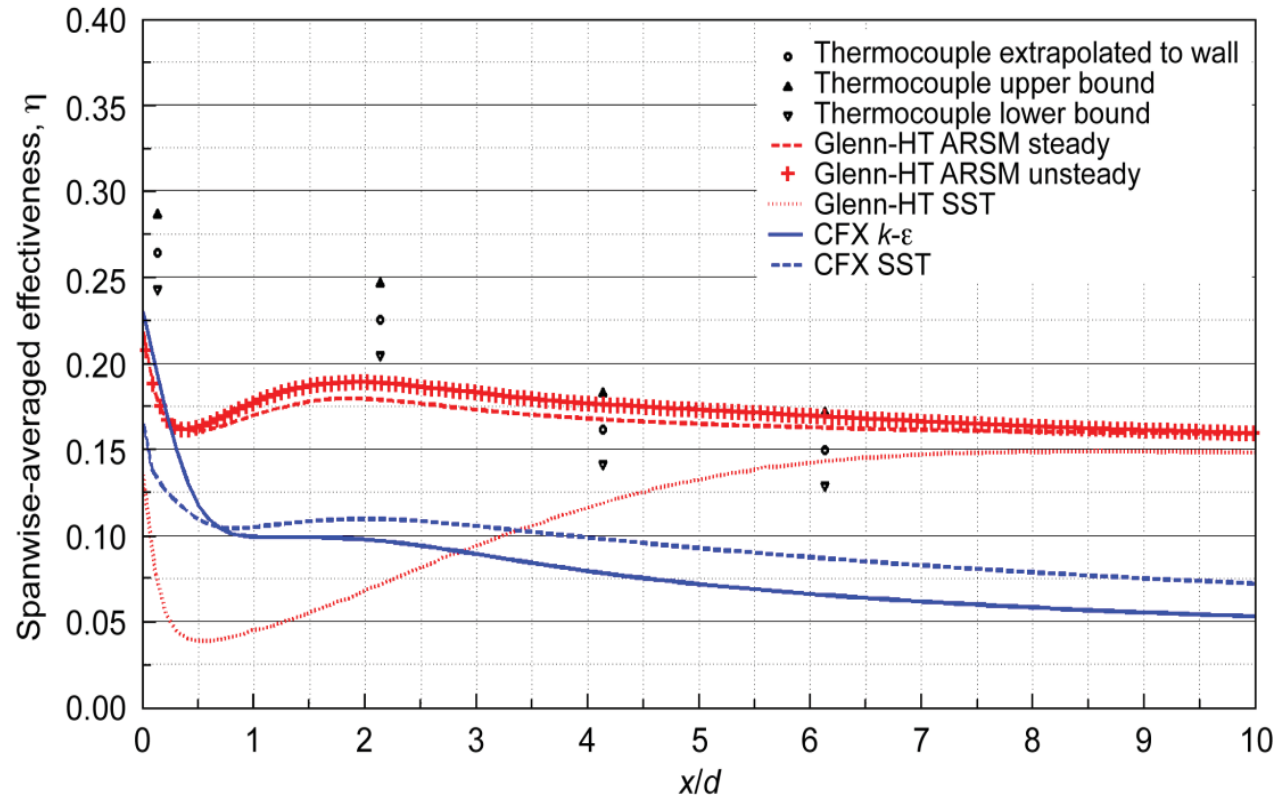
- One full hole modeled.
- Multi-block grid contained approximately 8 million cells.
- From 12 d's upstream to 16 d's downstream of the cooling hole.
- Spacing between the holes 3d's.
- Periodic b.c. in spanwise direction.
- Free-Stream b.c. at 5d's from the wall.
- Exit boundary condition specified at the outlet on the domain.
- The  $Tu$  (1.5 percent as measured) and a turbulence length scale were specified at the inlet.
- No particular handling of the inlet boundary condition to include unsteadiness for our TFNS computations was performed.

# Computational Details (Cont.)

- Multiple block groups were assigned to individual CPUs for balanced parallel computing.
- Smaller blocks were further consolidated to reduce communications overhead before implementing grouping.
- Initially 120 groups (CPUs) were used.
- It was possible to increase that number to 1200 for improved parallel capability.
- Grid refinement in areas near the no-slip walls and the cooling hole outlet and downstream of the cooling hole with wall shear-stress-scaled grid spacing of  $\Delta x^+ < 300$ ,  $\Delta y^+ < 3$ ,  $\Delta z^+ < 200$ .
- Grid cells in the film cooling flow core were constructed to be uniform and nearly cubic in shape.

# RANS and URANS

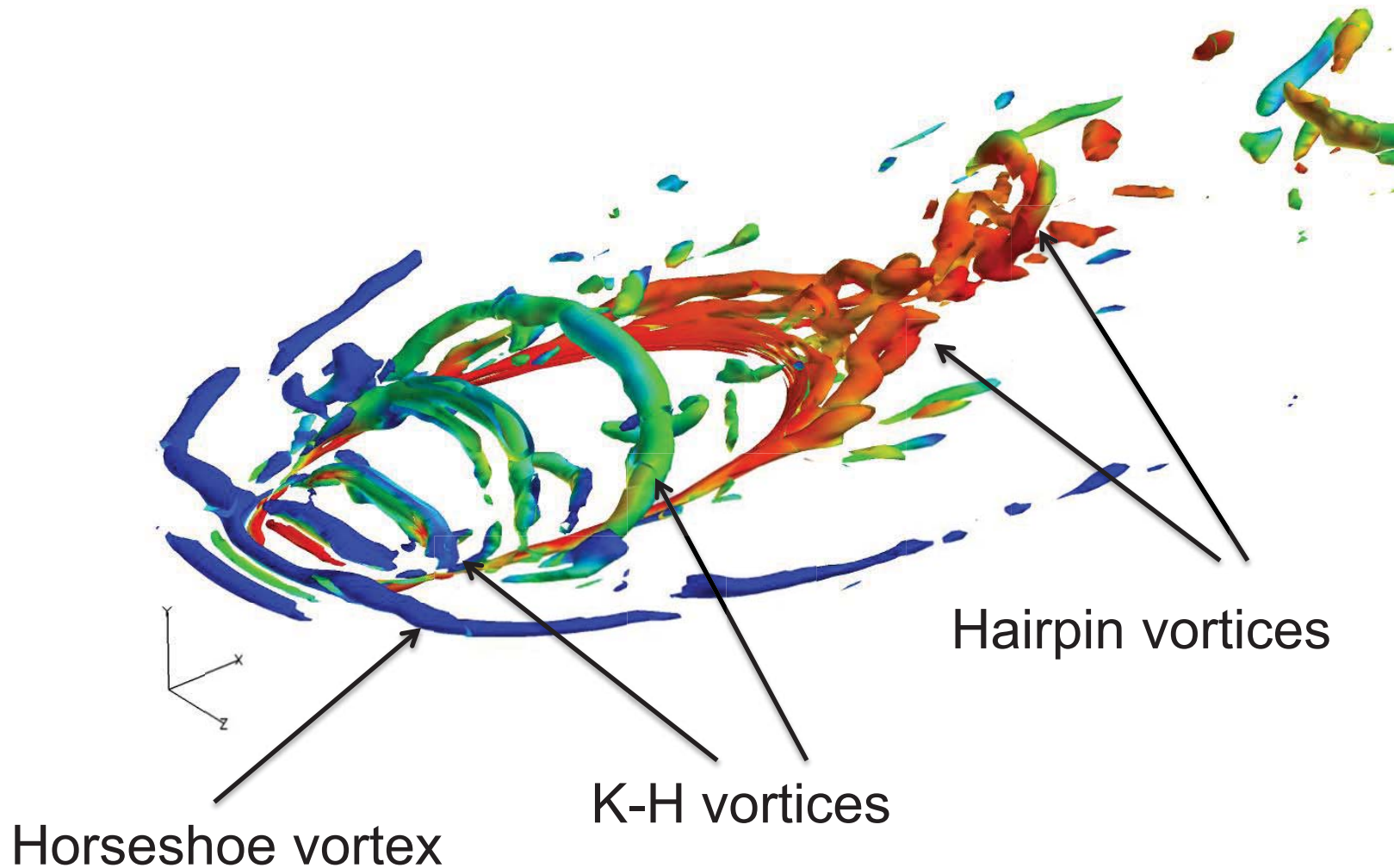
$$\eta = (T_{\infty} - T_{aw}) / (T_{\infty} - T_c)$$



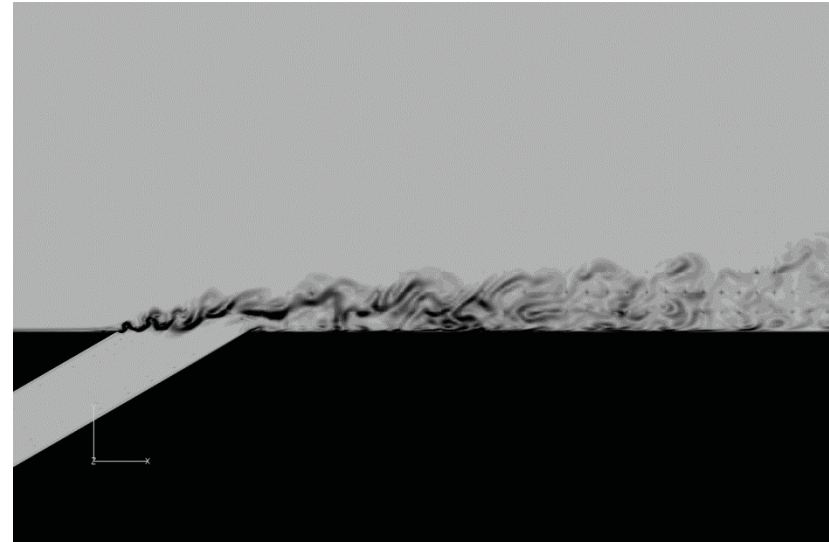
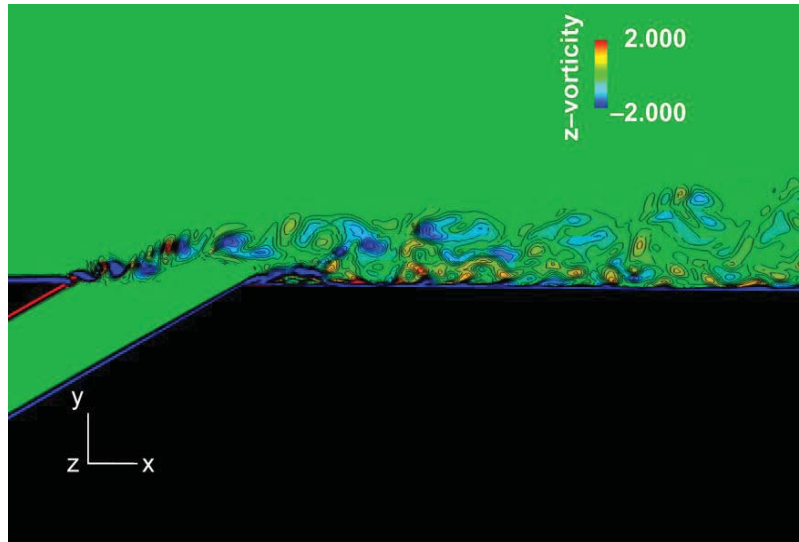
- For the  $M=1$ ,  $DR=1$  case, multiple computations were performed using RANS and URANS to show the variation in the results obtained and show the need to reduce the impact of turbulence models.



# TFNS Solutions- $M=0.5$ , $DR=1.0$



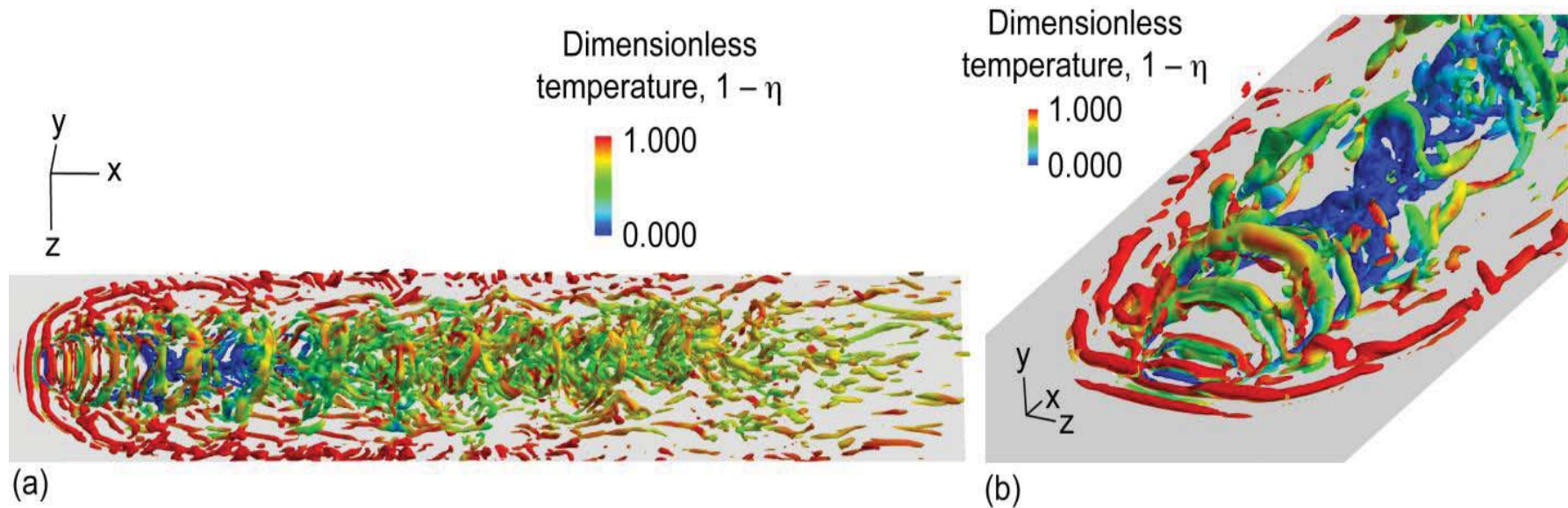
# TFNS Solutions-M=0.5, DR=1.0



- Figure shows , Z-vorticity and Density Gradient.

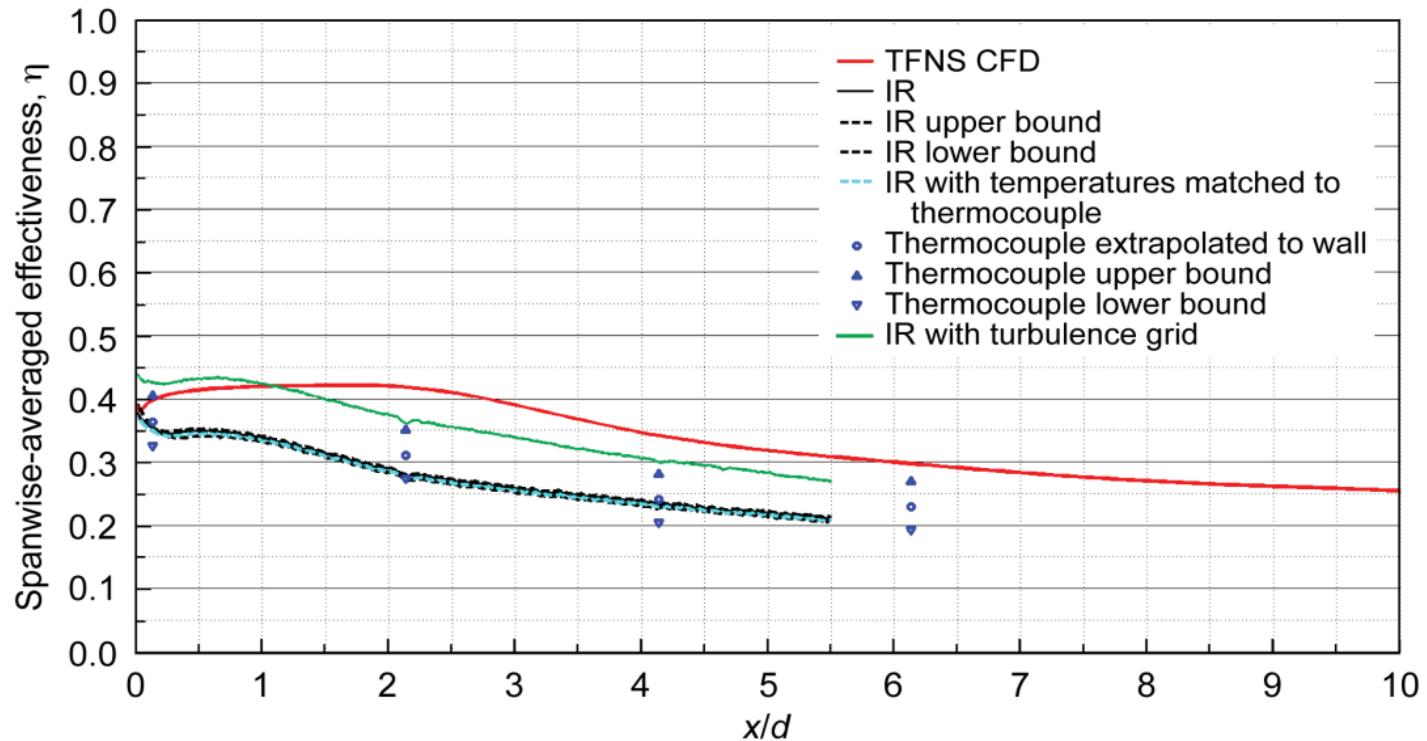


# TFNS Solutions- $M=0.5$ , $DR=1.0$



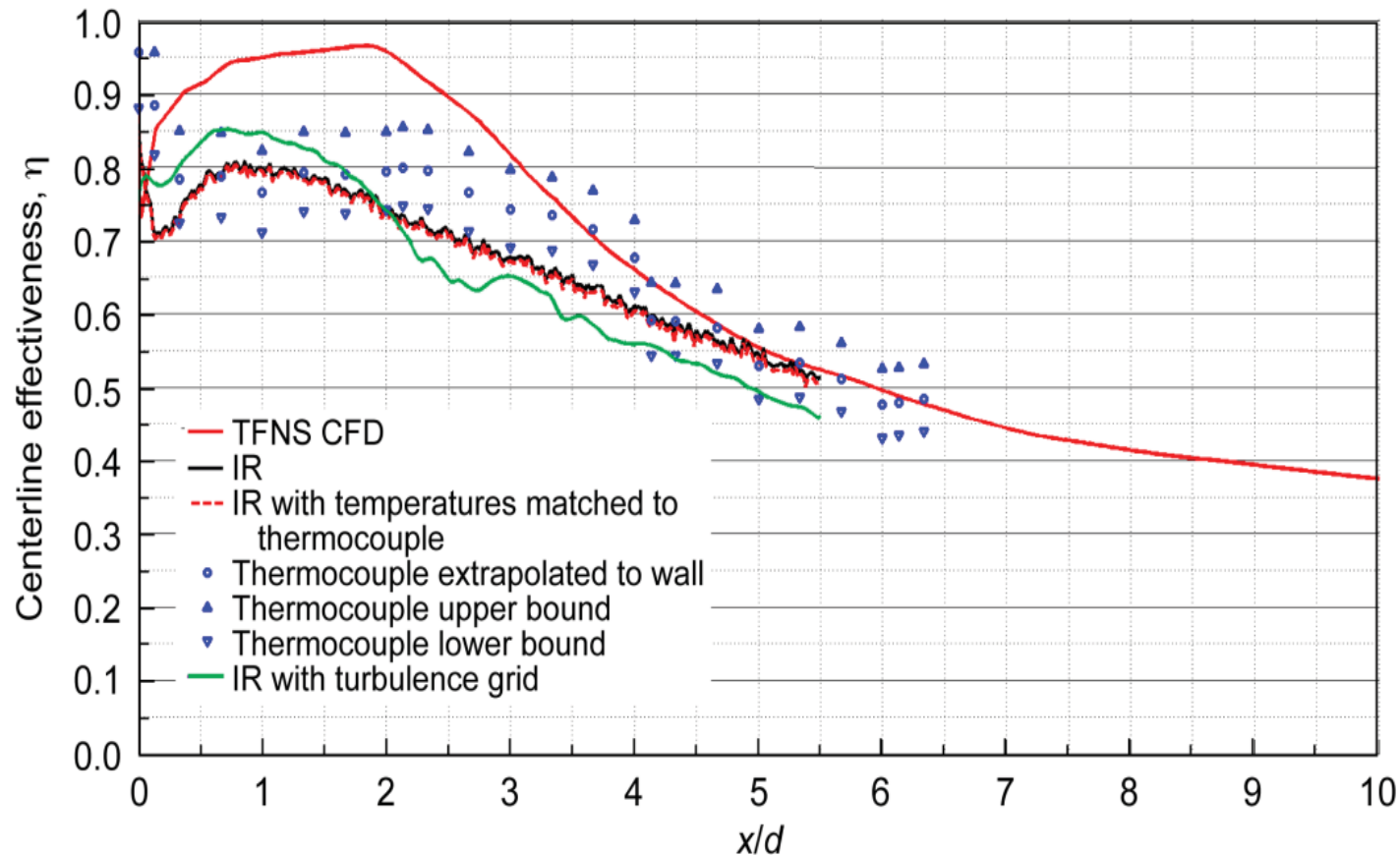
- Q-criterion isosurfaces of  $Q^* = 0.1$  at  $M = 0.5$  and  $DR = 1.0$ .
- Note the Kelvin-Helmholtz vortices.
- Hairpin vortices.

# TFNS Solutions-M=0.5, DR=1.0



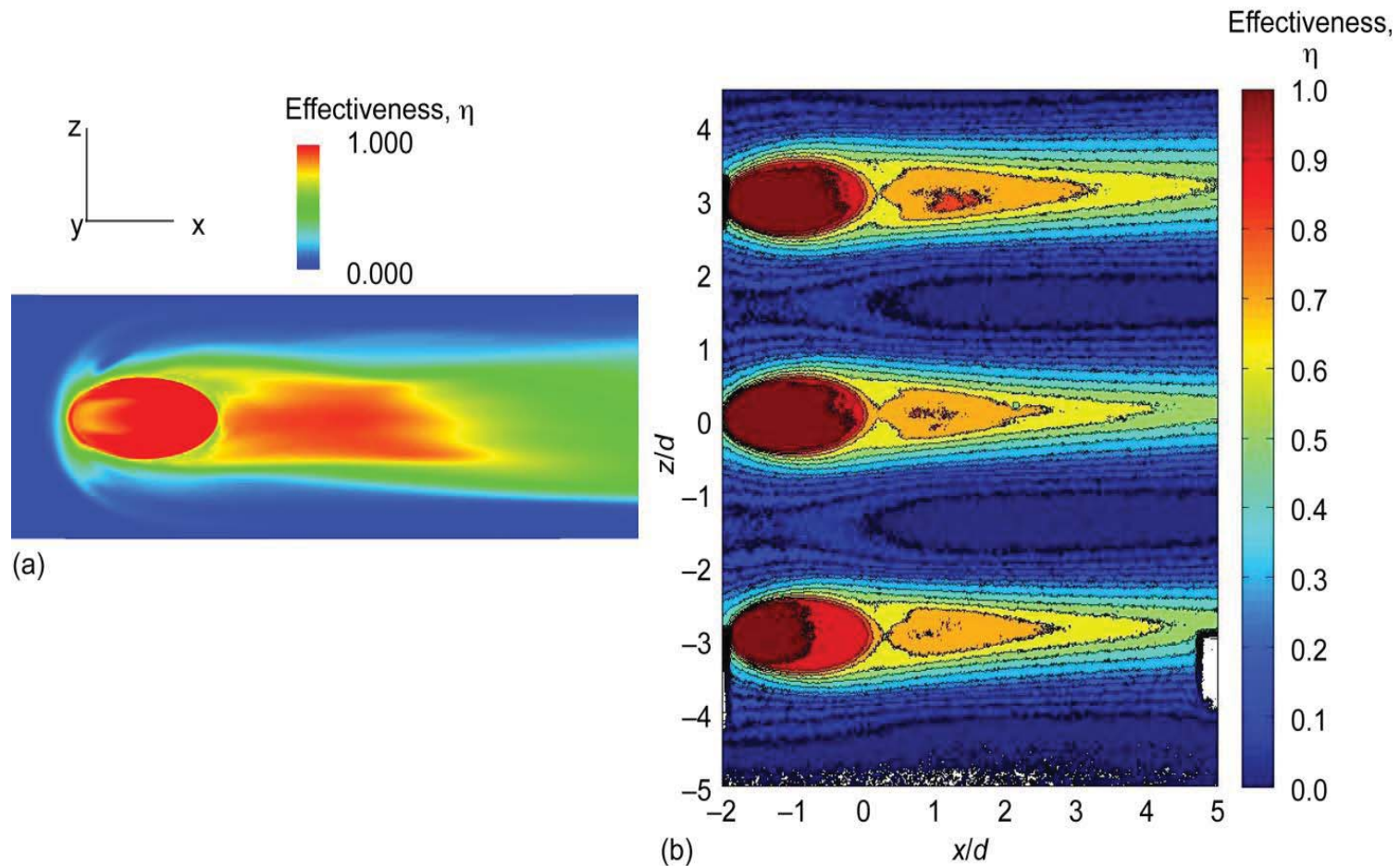
- Comparison to data shows over prediction!

# TFNS Solutions-M=0.5, DR=1.0



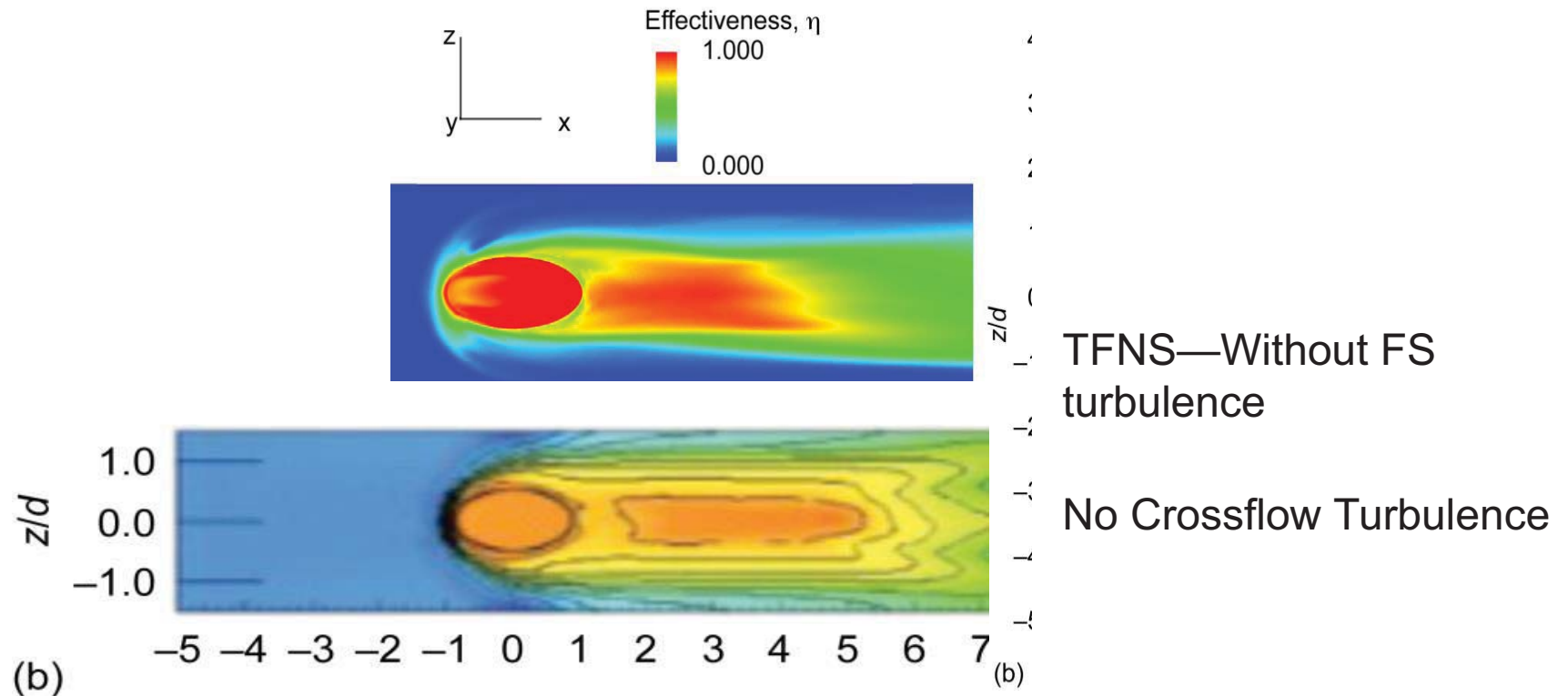
- Comparison to data shows over prediction!

# TFNS Solutions-M=0.5, DR=1.0



- Comparison to data shows over prediction!

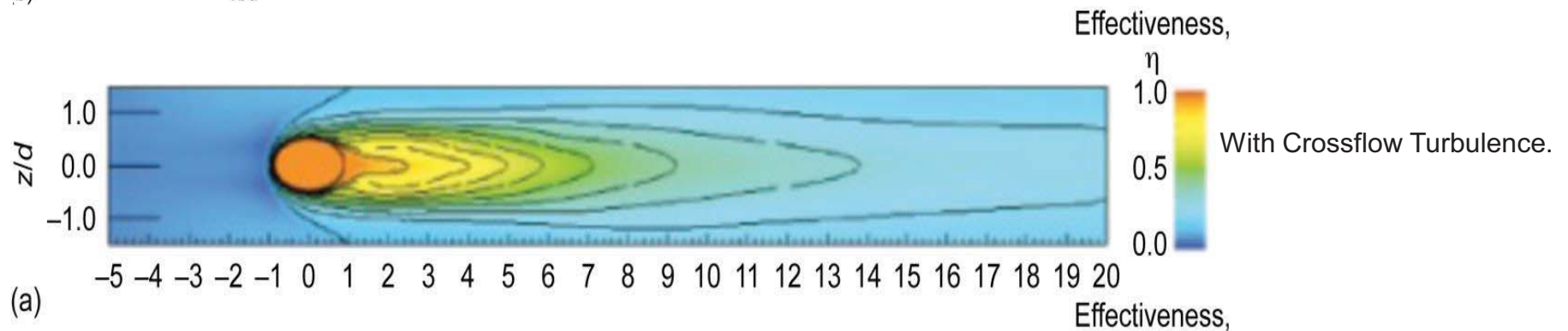
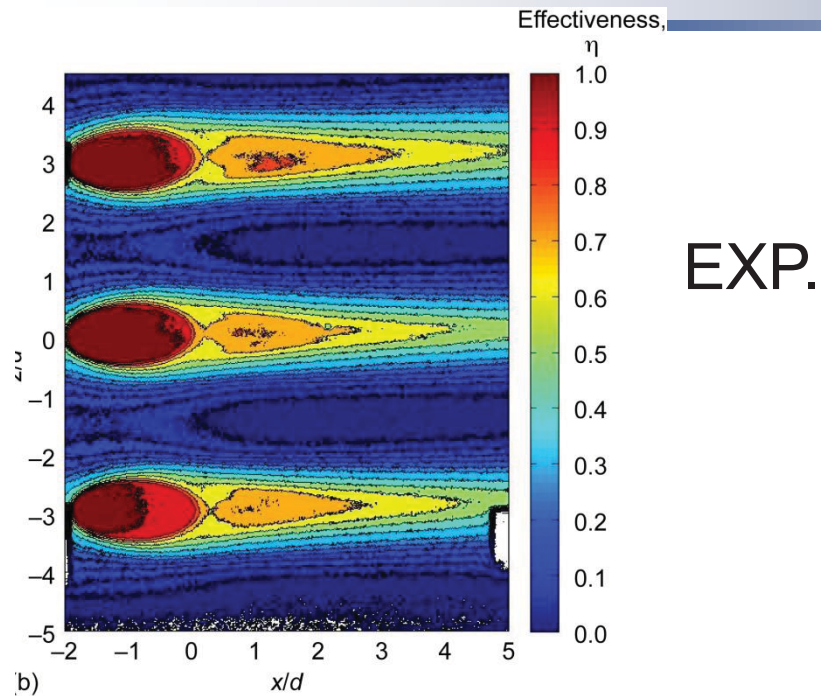
# TFNS Solutions-M=0.5, DR=1.0



Ziefle, J.; and Kleiser, L.: Numerical Investigation of a Film-Cooling Flow Structure: Effect of Crossflow Turbulence. J. Turbomach., vol. 135, no. 4, 2013, pp. 041001—041001—12.

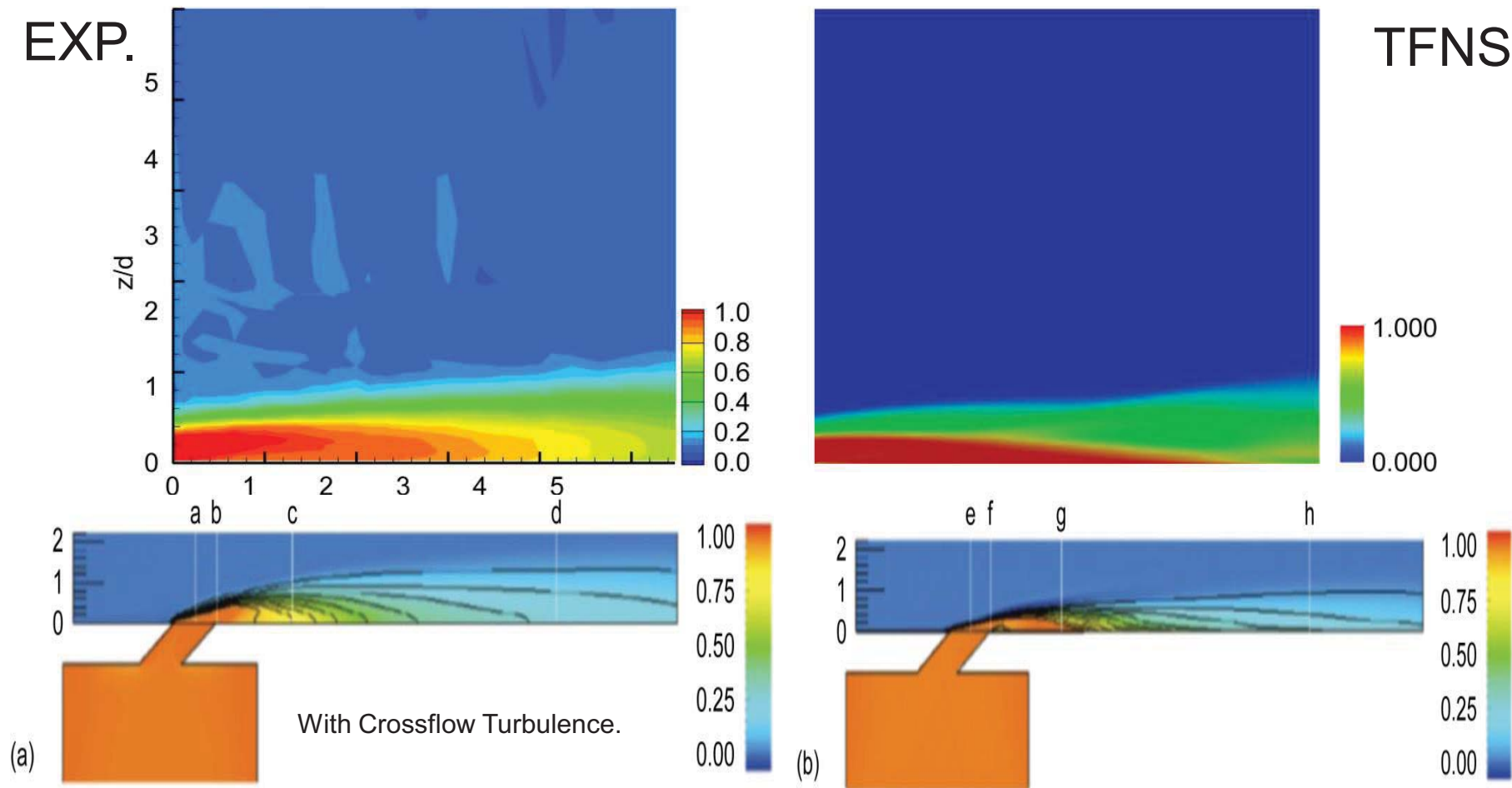


# TFNS Solutions-M=0.5, DR=1.0



Ziefle, J.; Kleiser, L.: Numerical Investigation of a Film-Cooling Flow Structure: Effect of Crossflow Turbulence. J. Turbomach., vol. 135, no. 4, 2013.

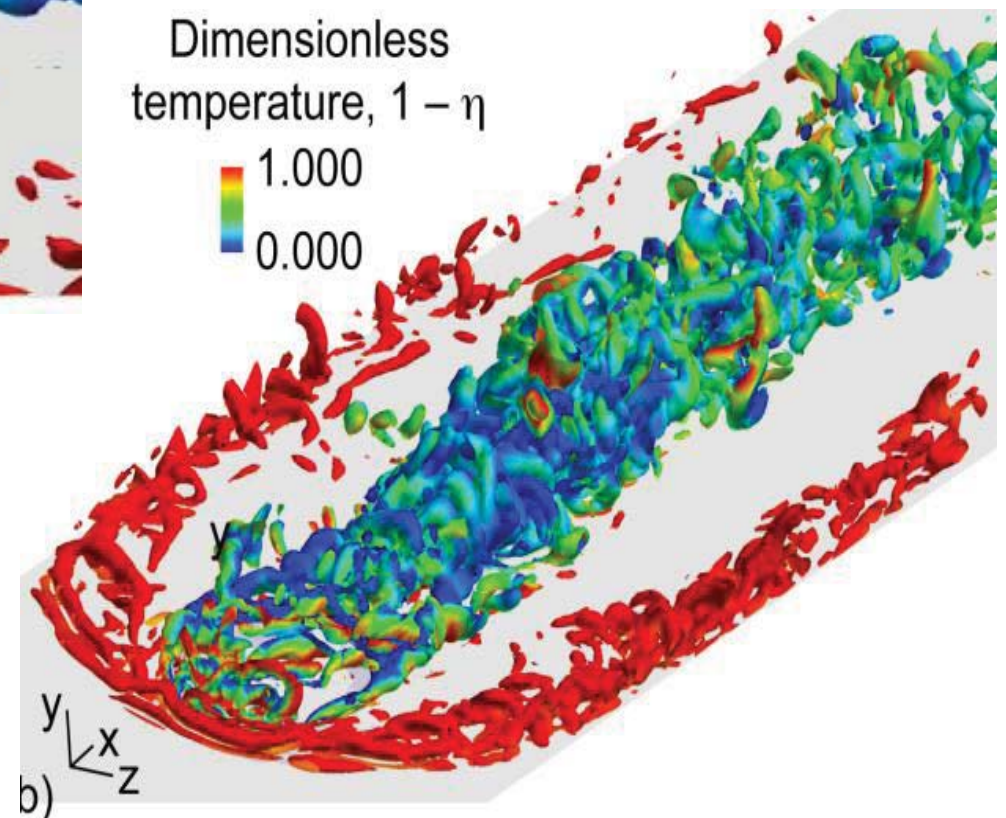
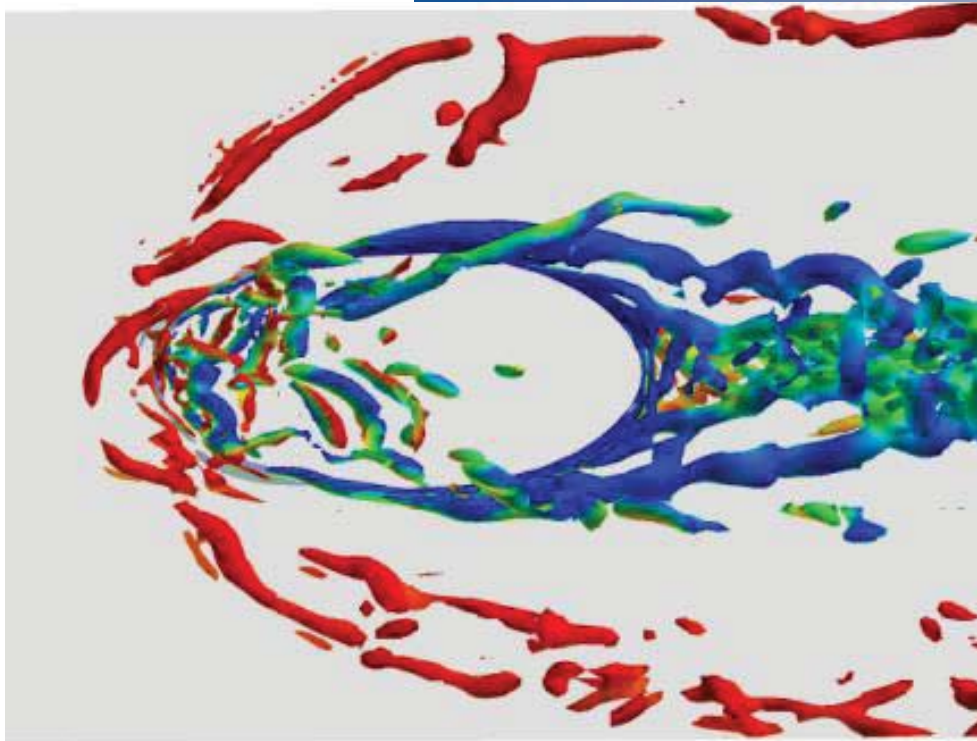
# TFNS Solutions-M=0.5, DR=1.0



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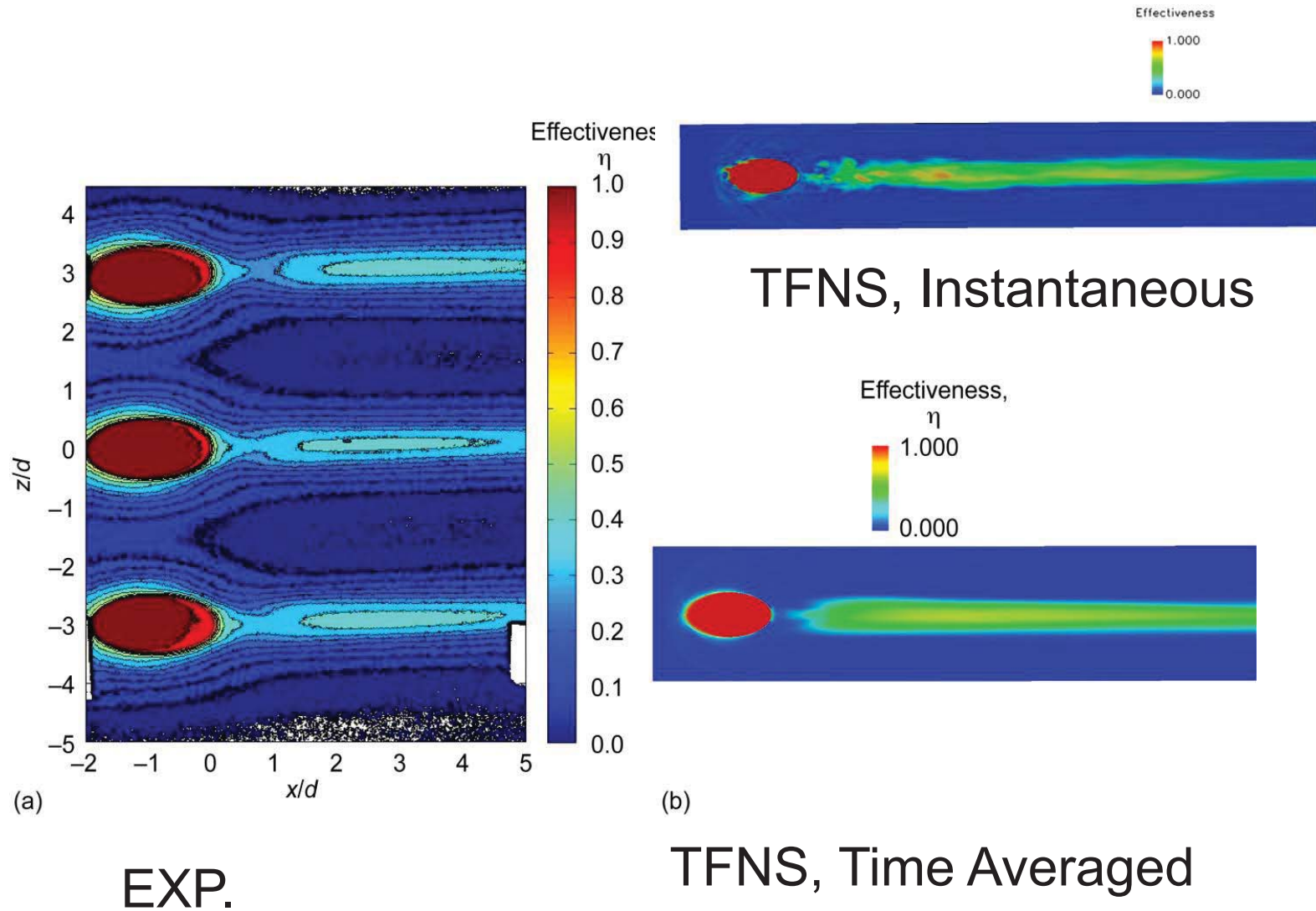
J. Turbomach., vol. 135, no. 4, 2013, pp. 041001—041001–12.

# TFNS Solutions-M=1.0, DR=1.0

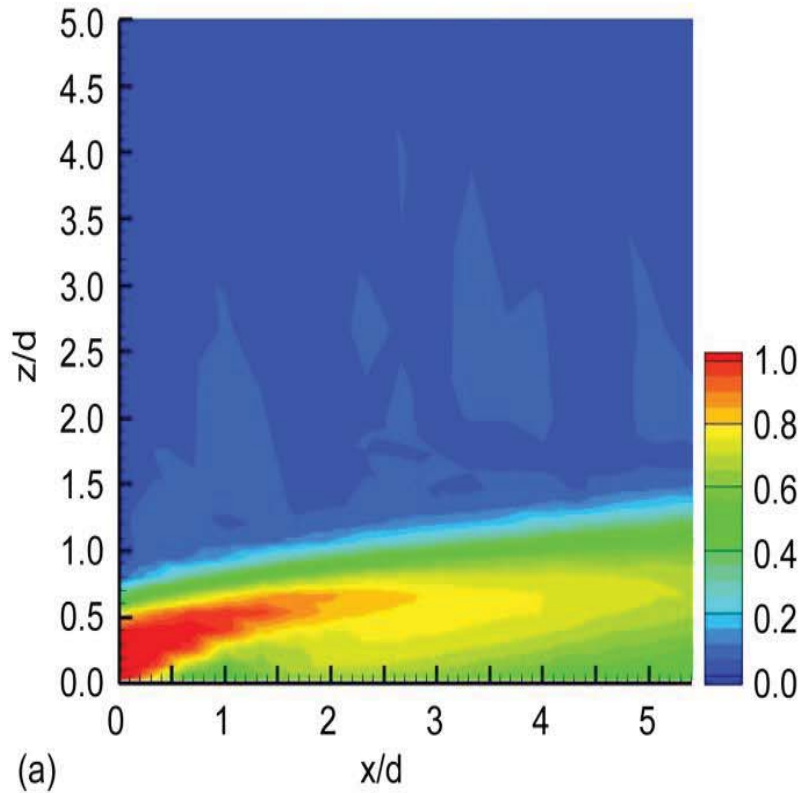




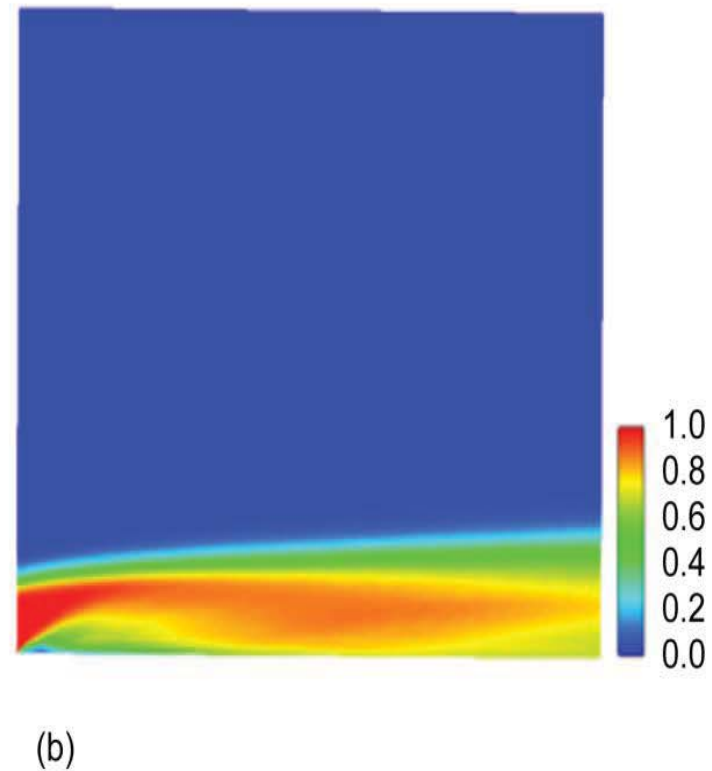
# TFNS Solutions-M=1.0, DR=1.0



# TFNS Solutions-M=1.0, DR=1.0

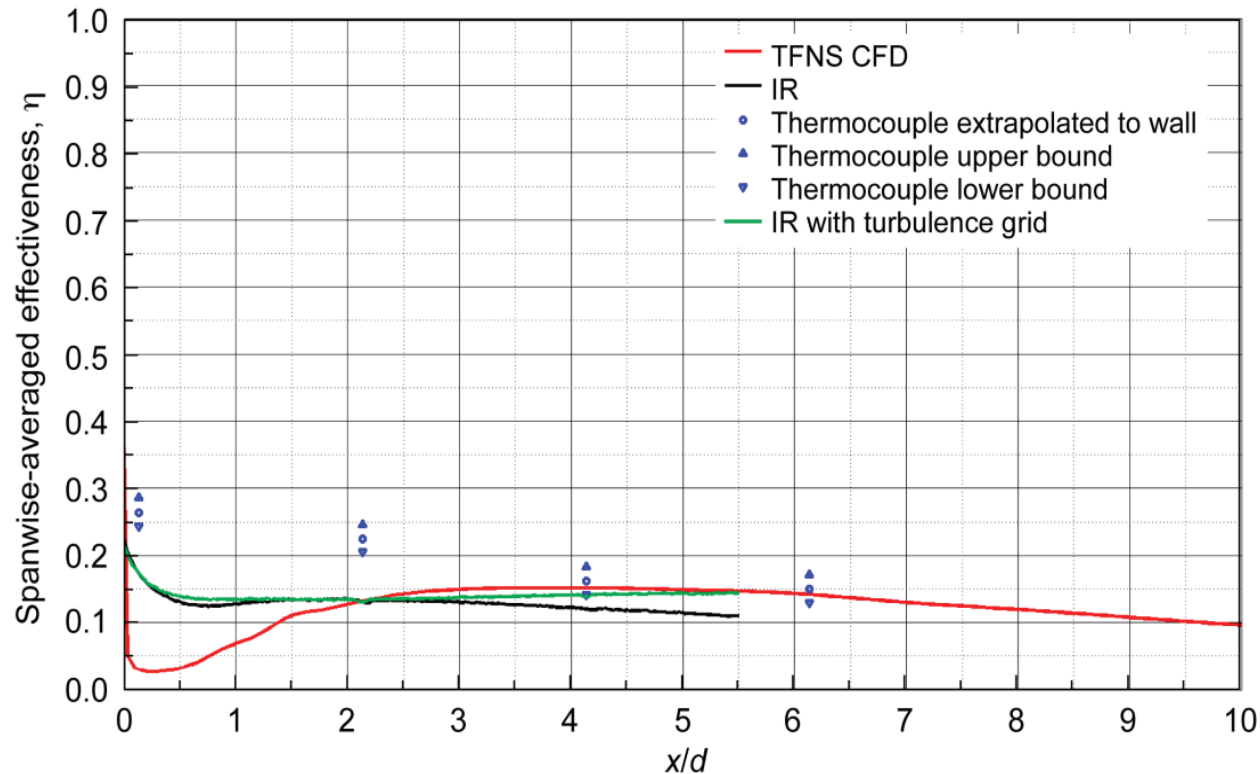


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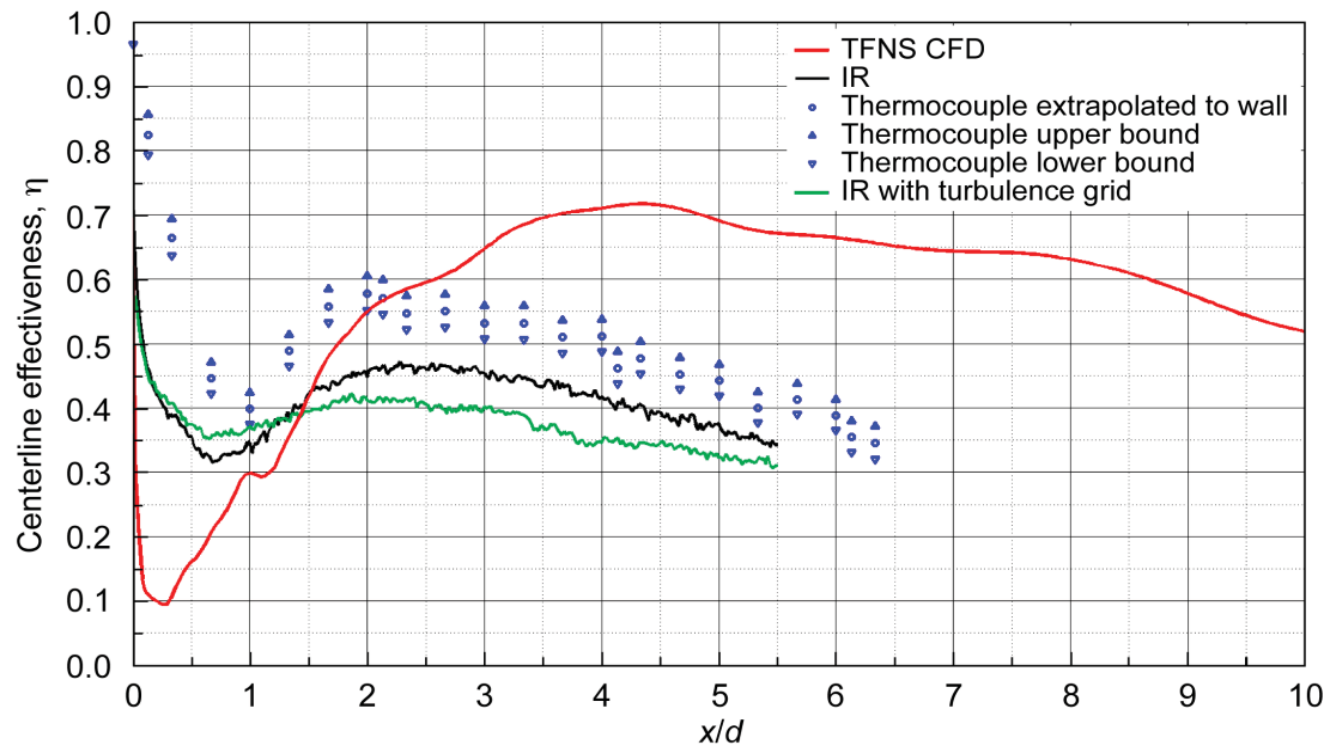
TFNS

# TFNS Solutions- $M=1.0$ , $DR=1.0$



Spanwise-averaged film effectiveness for  
 $M = 1.0$ ,  $DR = 1.0$ , and  $Tu = 1.5$

# TFNS Solutions- $M=1.0$ , $DR=1.0$



Centerline film effectiveness for  
 $M = 1.0$ ,  $DR = 1.0$ , and  $Tu = 1.5$

# Summary and Conclusions

- The Time-Filtered Navier-Stokes (TFNS) method was implemented in the Glenn-Heat Transfer (Glenn-HT) code.
- Analyses of a flat plate cooled by long holes inclined at  $30^\circ$  to the free stream were conducted to obtain both steady and unsteady flow solutions.
- The experimental data from an accompanying experiment.
- Results showed that RANS solutions are highly dependent on the turbulence model used and URANS does not provide a better alternative.

# Summary and Conclusions

- To reduce this dependence, the unsteady TFNS was used.
- Good resolution of the flow was achieved: K-H structures resulting from the interaction of the two streams and hairpin vortices among others can be observed.
- Good agreement was not achieved to the IR thermography.
- Based on the literature for the blowing ratio of 0.5, it was concluded that achieving a successful agreement requires accurate matching of the free-stream turbulence.
- Results of the TFNS, are consistent with computations performed in the literature without the effect of free stream and appropriate boundary conditions should be implemented in the flow solvers.